# CSE 120
# Principles of Operating Systems

## Spring 2023

## Lecture 10: Memory Management Overview

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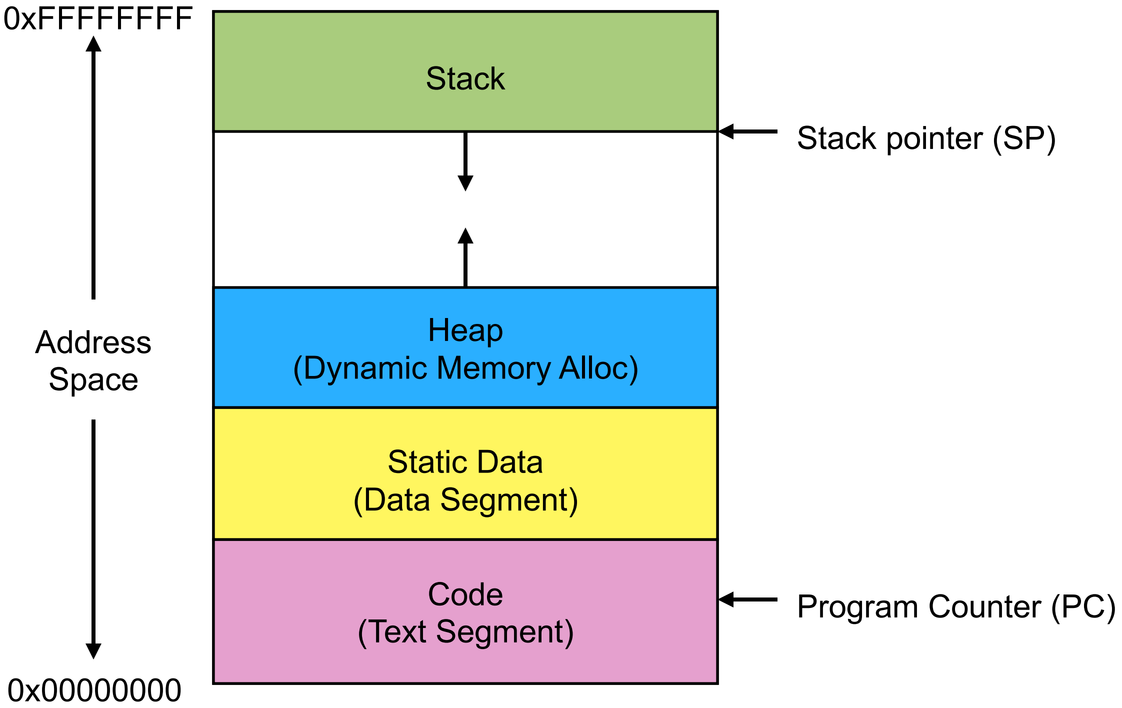
# Administrivia

- Grades are out for Homework #2 and Project 1
- Homework #3 released
- Project 2 released
  - You have already learned enough to do tasks 0 and 1
  - Today we'll dive into memory management
  - Do the VM worksheet (HW 3) before starting on task 2

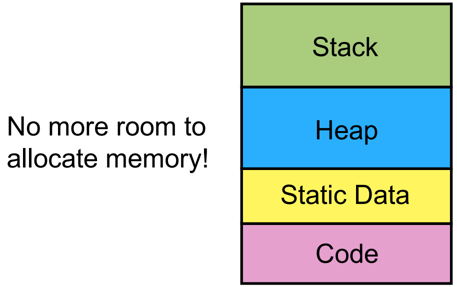
# Basic Process Address Space

How can we share the memory on one server amongst many processes?



# Memory Management Challenges

- Finite memory capacity
  - My process' data might not fit in physical memory
  - Might run many processes at once
- Locating data in memory
  - Where is each processes' data located in memory?
- Protection
  - Processes should not be able to read or write each others' memory
  - Processes should not be able to corrupt OS memory
- Efficiency
  - Should support many processes at once



# Memory Management Overview

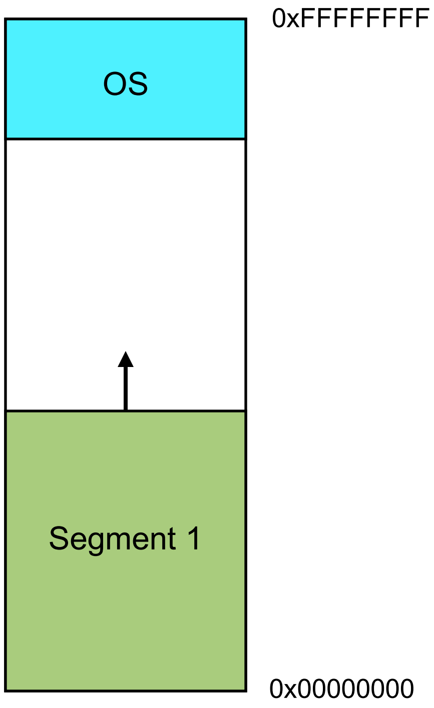
- New few lectures are going to cover memory management
- What goals are we trying to achieve?
  - Multitasking, transparency, isolation, and efficiency
- What mechanisms can we use to achieve those goals?
  - Physical and virtual addressing
  - Partitioning, segmentation, paging
  - Page table management, TLBs, VM tricks
- What policies?
  - Page replacement algorithms

# Today's Outline

- Virtual memory
  - The abstraction that the OS provides for managing memory
- Evolution of memory-management techniques
  - From fixed segments to paging today

# Single-tasking

- In the early days: run one process at a time
  - OS loads a process, runs it, unloads it, loads the next process…
- Highest memory holds the OS
- Process is allocated memory starting at 0
  - Includes code, data, stack, heap
- Programs use physical addresses directly
- What are the problems with this approach?

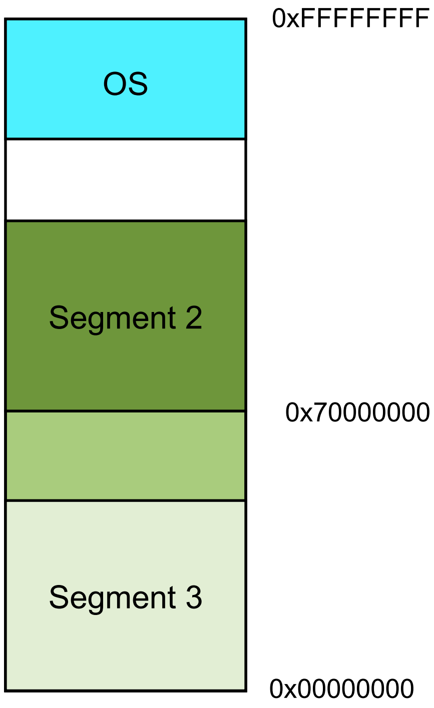


# Memory Management Goals

- Multitasking
  - Allow multiple processes to be in memory at once
- Transparency
  - Convenient abstraction for programming
  - Processes should not know that memory is shared
  - Processes should run regardless of the number/locations of processes
- Isolation/protection
  - Processes shouldn't be able to corrupt each other (or the OS)
- Efficiency
  - CPU and memory utilization shouldn't be degraded badly by sharing

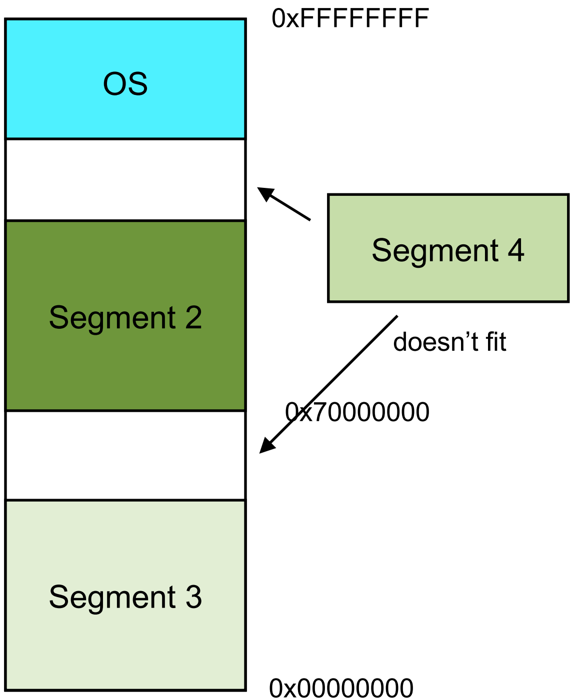
# Multi-tasking with Static Relocation

- Support multiple processes by relocating once at load time
- Highest memory holds the OS
- When a process is loaded
  - Allocate a region of memory
  - Loader rewrites all memory addresses to relocate the process
- What are the problems with this approach?



# Multi-tasking with Static Relocation - Limitations

- Problems with static relocation:
  - No protection (between processes or of OS)
  - Low memory utilization
    - Addresses are fixed after loading
    - Cannot relocate at runtime to fill holes
  - No sharing
    - One segment per process
    - Cannot share parts of the process address space
  - Entire address space needs to fit in memory



# Dynamic Memory Relocation

- Change addresses dynamically during every memory reference
- Virtual addresses
  - Processes use virtual addresses to refer to memory locations
  - These addresses are translated to physical addresses during every memory reference
  - Virtual addresses are independent of the physical location of the referenced data
- Address translations
  - OS decides where to place data in physical memory
  - Translate from virtual to physical addresses using hardware (memory management unit)

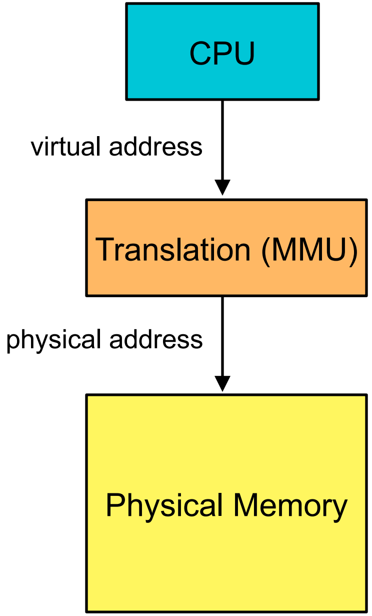
# Virtual Memory

- The abstraction that the OS provides for managing memory is virtual memory
- Two views of memory, called address spaces:
  - Virtual address space (seen by program)
  - Physical address space (actual allocation of memory)
- Virtual address space often much larger than physical address space
  - 64-bit addresses
- Benefits:
  - Flexible – OS can move processes around in memory as they execute
  - Transparent – hardware handles address translation
  - Protection – can check for isolation during address translation
  - Efficiency – use memory efficiently

# (Live Demo of Virtual Memory)

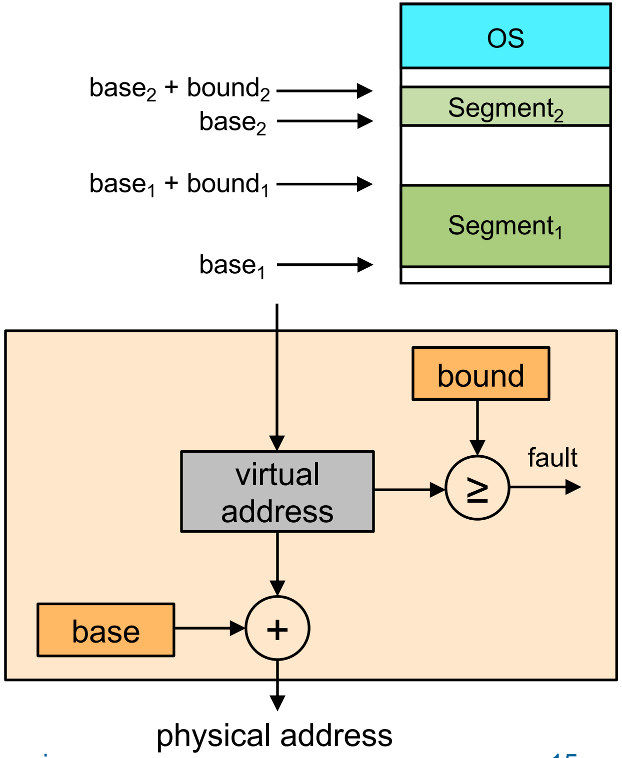
# Address Translation

- Translation table set up by the OS in software
  - Mappings from virtual to physical addresses
- Dedicated hardware performs the address translations
  - Memory management unit (MMU)
  - Translates for each load and store
- Many ways to do address translations:
  - Base and bound
  - Segmentation
  - Paging



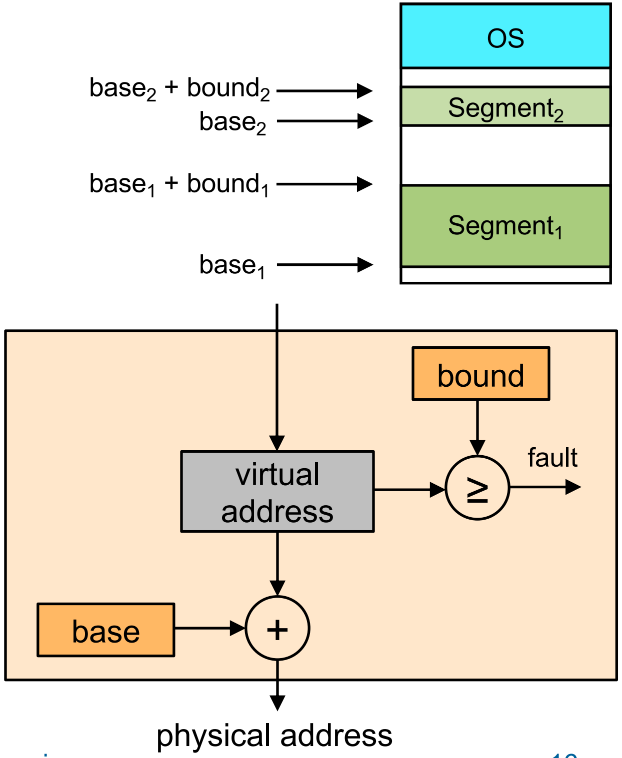
# Base and Bound

- 2 hardware registers: base and bound
- A process can only access physical memory in [base, base+bound)
- On a context switch:
  - Save/restore base and bound registers
- Built in Cray-1 (1976)
- Benefits:
  - Simple, fast translation, cheap
  - Can relocate a segment at execution time
  - Bound register provides protection



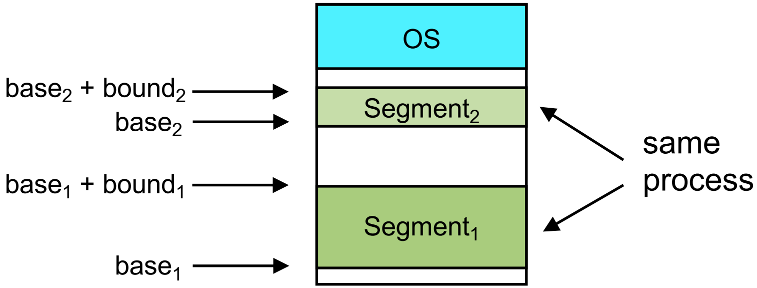
# Base and Bound - Limitations

- Problems with base and bound:
  - Fragmentation – it's hard to use memory efficiently
    - » Wasted memory between segments (external fragmentation)
    - » Wasted memory within a segment (internal fragmentation)
  - Cannot share memory between processes



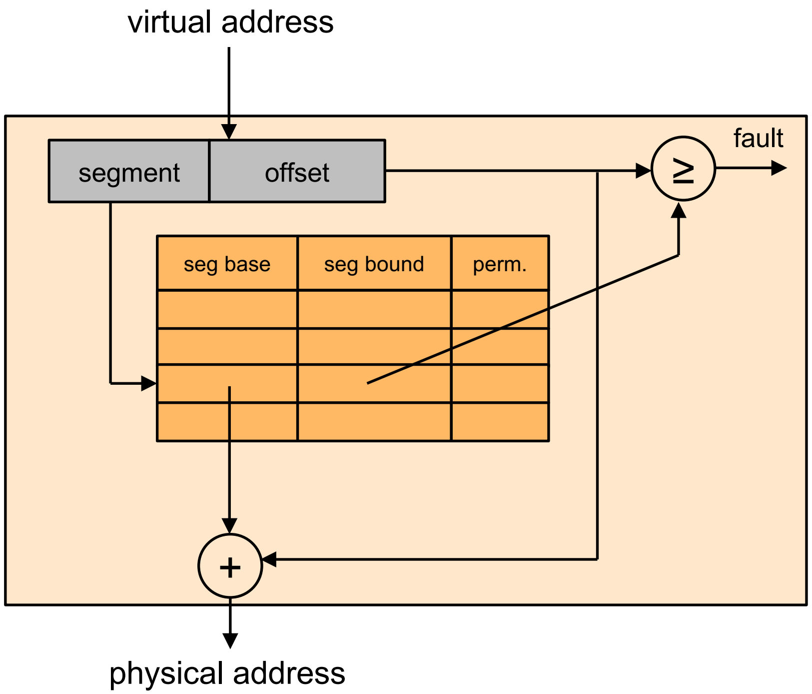
# Segmentation

- Split each process' virtual address space into multiple segments
  - Segment: variable-sized area of memory
- Natural extension of base and bound
  - Base and bound: 1 segment per process
  - Segmentation: many segments per process



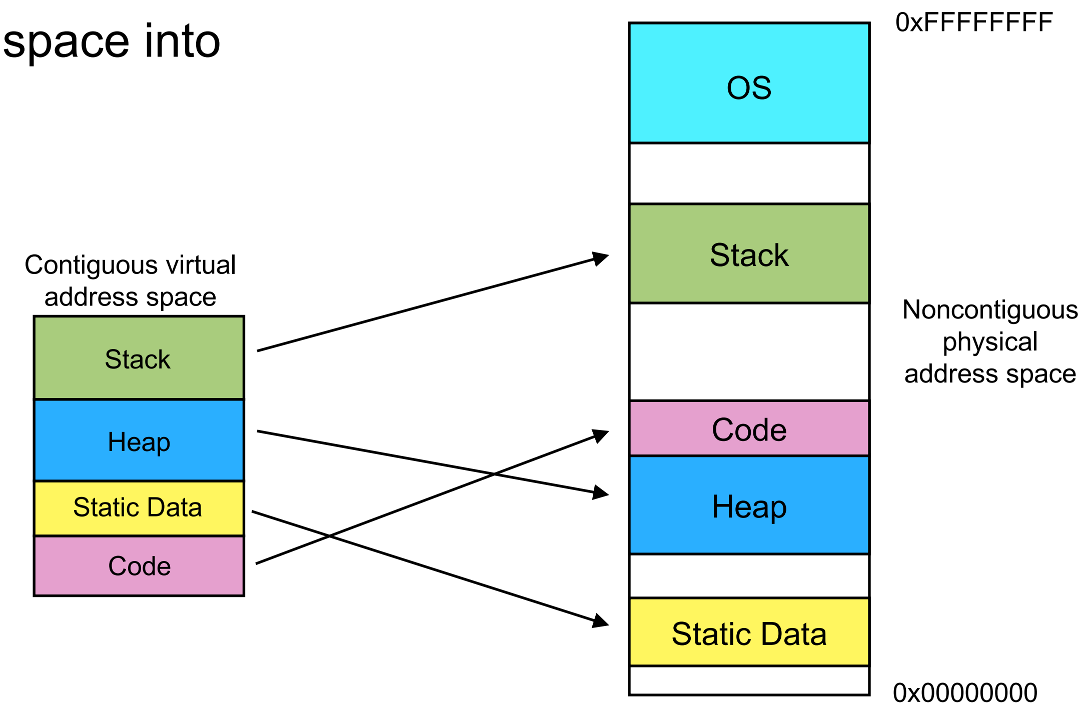
# Segmentation – Address Translation

- Segment map
  - One per process
  - Holds base and bounds registers, permissions for each segment
- Context switch
  - Save/restore table or pointer to table in kernel memory



# Segmentation Example

- Split process's virtual address space into stack, heap, static data, code

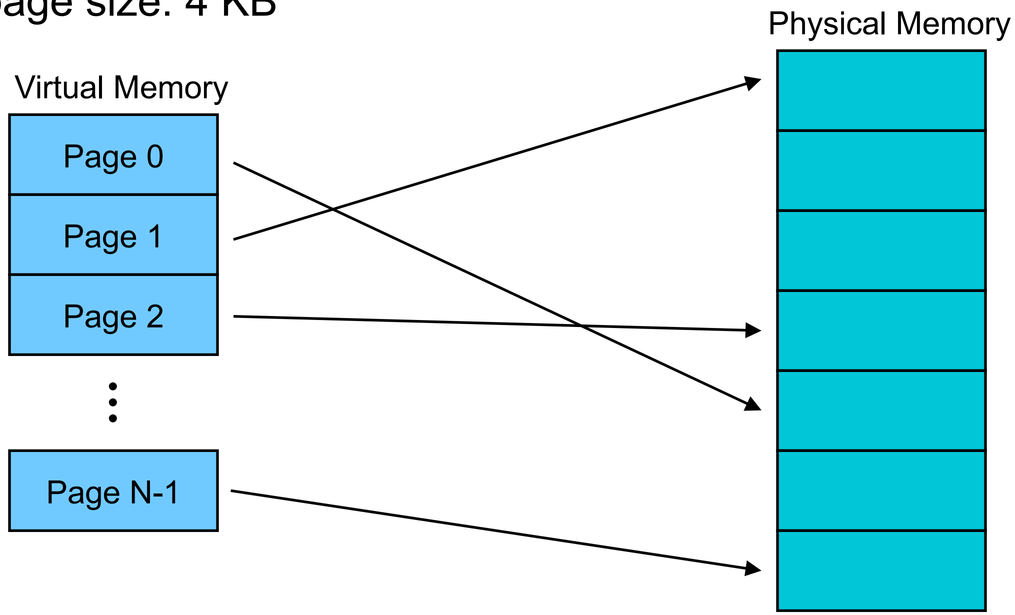


# Segmentation - Tradeoffs

- Benefits:
  - Process memory can be split among several segments
    - Allows sharing of some segments between processes
  - Flexible: segments can be assigned, moved, grown, shrunk, or swapped independently
- Limitations:
  - Fragmentation
    - External fragmentation – can still have holes in physical memory due to different sized segments
    - Internal fragmentation – each segment can be large and have regions that are unused
  - Large segment tables can be complex to manage

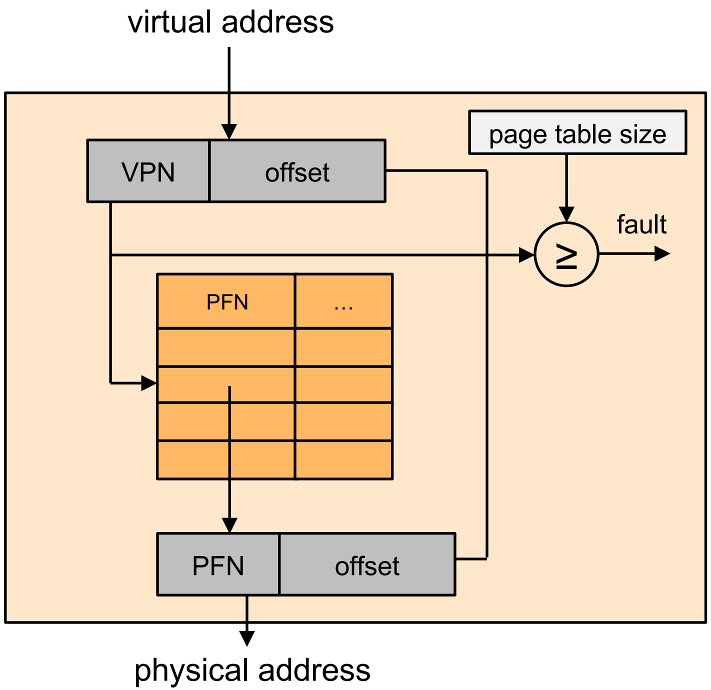
# Paging

- Divide physical and virtual memory into fixed-sized chunks calls pages
  - Common page size: 4 KB



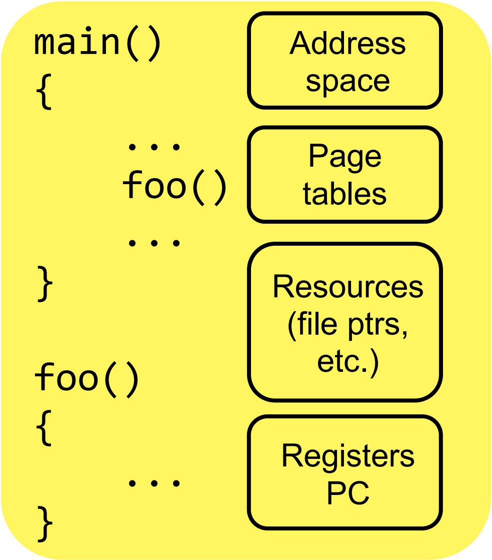
# Paging – Address Translation

- Virtual addresses
  - Two parts: virtual page number (VPN) and offset
- Page tables
  - Map virtual page number to page frame number (PFN)
    - » The physical page number
  - Permissions, etc.
  - Use the VPN as an index into the page table
- Use concatenation instead of addition
  - Possible due to fixed power-of-2-sized pages



# Page Tables

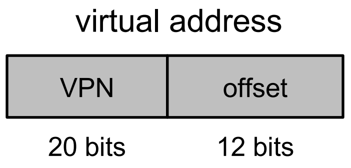
- Page tables are per process
  - Each process maintains its own page tables
  - On a context switch:
    - » Switch which page tables are used for translation




Process

# Paging Example

- Pages are 4 KB
  - Offset is 12 bits ($2^{12}$ = 4096)
  - Assume 32 bit system
  - Leaves 20 bits for VPN ($2^{20}$ VPNs)
- Example virtual address: 0x00007468
  - Virtual page is 0x7, offset is 0x468 (lowest 12 bits of address)
- Suppose page table entry 0x7 contains 0x2
  - Page frame number is 0x2
  - Seventh virtual page is at address 0x2000 (physical page 2)
  - Physical address = 0x2000 + 0x468 = 0x2468



# Paging - Advantages

- Easy to allocate memory
  - Memory comes from a free list of fixed-size chunks
  - Allocating a page is just removing it from the list
  - External fragmentation is not a problem
- Easy to swap out chunks of a program
  - All chunks are the same size
  - Use valid bit to detect references to swapped pages

# Paging - Limitations

- Can still have internal fragmentation
  - Process may not use memory in multiples of pages
- Memory reference overhead
  - 2 references per address lookup (page table, then memory)
  - Solution – use a hardware cache of lookups (more later)
- May need a lot of memory to hold the page tables
  - Need one page table entry per page
  - 32-bit address space with 4 KB pages = $2^{20}$ page table entries
  - 4 bytes per entry = 4 MB per page table
  - 25 processes = 100 MB just for page tables
  - Solution – hierarchical pages tables (more later)

# Memory Management Summary

- Virtual memory
  - Processes use virtual addresses
  - Hardware translates virtual address into physical addresses with OS support
- Evolution of memory-management techniques
  - Single, fixed physical segment per process (no virtual memory)
  - Single segment per process, static relocation (no virtual memory)
  - Base-and-bound – dynamic relocating of entire process
  - Segmentation – multiple (variable-sized) segments with dynamic relocation
  - Paging – small, fixed size pages

# For next class…

- Read chapters 18-20